AD NUMBER

AD273610

NEW LIMITATION CHANGE

TO

Approved for public release, distribution unlimited

FROM

Distribution authorized to U.S. Gov't. agencies and their contractors; Foreign Government Information; 13 JUN 1961. Other requests shall be referred to British Embassy, 3100 Massachusetts Avenue, NW, Washington, DC 20008.

AUTHORITY

DSTL, DSIR 23/28767, 22 Jul 2009

AD 273 610

NOTICE: When government or other drawings, specifications or other data are used for any purpose other than in connection with a definitely related government procurement operation, the U. S. Government thereby incurs no responsibility, nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use or sell any patented invention that may in any way be related thereto.

UNCLASSIFIED

A.R.C.22,930
Hyp.194

A.R.C.22,930
Hyp.194

AERONAUTICAL RESEARCH COUNCIL

THE MEASUREMENT OF TEMPERATURE IN AN ARGON SHOCK TUBE BY MICROWAVE NOISE RADIATION

By

D. Walsh,
Oxford University

13th June, 1961

'A.1' REPORT

UNCLASSIFIED

A.R.C. 22,930 AERONAUTICAL RESEARCH COUNCIL A.R.C. 22,930

Hyp.194 HYPERSONICS SUB-COMMITTEE Hyp.194

The Measurement of Temperature in an Argon Shock Tube by Microwave Noise Radiation

- By -
D. Walsh*
University of Oxford

13th June, 1961

1. Introduction

Temperatures of shock waves have been measured by spectroscopic techniques or thin film bolometers. These methods have some limitations. It appeared that a microwave measurement would be interesting to try, and might even have some advantages over other methods, particularly in that the response time of the receiver would be short. This possibility had been suggested some time ago[1], but to the author's knowledge has not been tried out previously.

Noise is radiated at all frequencies from a hot plasma. The most noise power that can be radiated into a microwave receiver is kTB, where k is Boltzmann's constant, T is the temperature of the plasma and B the receiver bandwidth. This power will be reduced by an emissivity factor that describes how good a black body the plasma is at the microwave frequency used. The microwave problem is to choose frequencies and waveguide horns so that the receiver will match to the plasma reasonably well. Then the received signal should reveal the temperature variation over a shock wave in one observation. The lower limit of detectable temperature should be the thousand degrees or so that is necessary to give appreciable ionisation (the microwave receiver sees noise radiated by electrons of course); there should be no upper limit.

There is one obvious difficulty. Receivers of sufficient sensitivity to detect a few thousand degrees can easily be constructed only in wavebands where mixer crystals and reliable local oscillators are available, for example the 3 cm and 8 mm bands. Interesting plasmas in hypersonic flight investigations have electron densities of 10^{15} per cc and upwards. This corresponds to a plasma (or critical) frequency of 300 kmc/s (1 mm wavelength). Hence a very poor match might be expected to available receivers.

It has been shown experimentally that this is not so. In a later section the reasons why a 3 cm signal can be matched to a high electron density plasma are set out under some simplifying assumptions. Briefly there are two reasons why matching is possible:

(i) The electron density is zero at the edge of the plasma and increases steadily to a maximum at the centre (for a cylindrical plasma).

(ii) For high electron-atom collision frequencies the plasma resonance effect is heavily damped. The real dielectric constant, which if there are no atoms present passes through zero and goes negative, never reaches zero if there is some damping.

2./

---

* This work was done during a vacation consultancy in the Aerodynamics Division of the N.P.L.

2. The Shock Tube

The experiments were conducted with the 2 in. shock tube previously used for other microwave work at the National Physical Laboratory[1]. The gas chosen was argon, since the calculated values[2] for temperature were expected to be more accurate than for more complicated gases. The range of pressures used, together with the measured Mach numbers and calculated electron density[2] is given in Table 1.

3. Microwave Considerations

The test section of the shock tube was a length of perspex tube 6 cm outside diameter. A pair of brass tapers were available from 3 cm waveguide. They enclosed the perspex tube, so that it passed through holes in the two sides tapering from the narrow guide face, whilst the broad face was continuous. The problem was to match the plasma through the perspex and along the horns in a measurable way. It would not matter if the match were not perfect provided it could be measured.

It is quite simple to measure the fraction of the microwave signal transmitted and reflected by the shock down the waveguides. The remaining fraction is assumed to be the absorption coefficient and this figure is also used as the emissivity for the temperature correction. Unfortunately any signal that leaks out of the horns down the shock tube appears to be absorbed in this measurement. In fact this is a crucial weakness of microwave measurements on high power plasmas of all kinds. Low power plasmas can often be entirely included inside a cavity resonator and there is no ambiguity. But as soon as substantial holes have to be made in the microwave system to let in the energy there is a chance of microwave power leaking out in a manner difficult to measure. This is doubly unfortunate for a temperature measurement, since some of the noise signal may be lost down the holes, and with an overestimated emissivity the final temperature will be further underestimated.

There are considerable difficulties in measuring signal lost down the shock tube so it was decided to try to reduce this to negligible proportions. Straightforward radiation from the holes should take place predominantly with the wave polarised as in the waveguide mode. Hence thin vanes were placed inside the shock tube so that their separation was narrower than the cut-off dimension. Spring steel vanes 0.004 in. thick were rapidly destroyed by the shock and this scheme had to be postponed.

Another mode of exit could be a coaxial mode propagating with the shock as inner conductor. This mode was inhibited by cylindrical groove quarter wavelength chokes around the holes. Absorption coefficients measured before and after these were fitted were consistent with a very slight reduction in power loss.

4. The Experiment

The shock tube was evacuated, filled to 20 cm of cylinder argon and pumped down to the pressures given in Table 1. An 18 s.w.g. aluminium diaphragm was used. The high pressure chamber was filled steadily with hydrogen until the diaphragm burst at around 1180 p.s.i. The Mach number was measured for each shock with two resistance thermometers spaced along the tube, which started and stopped a counter chronometer.

To measure the emissivity a low power 3 cm microwave signal was fed into the horn. A crystal on the other horn monitored power transmitted through the working section. Reflected power was measured with a directional coupler and crystal in the input side. Both crystals had 6 dB pads before them. The oscillator was protected from pulling with an isolator and 10 dB pad. With no plasma present, the insertion loss was 1.3 dB and the input V.S.W.R. 1.2. Typical reflection and

transmission/

transmission traces are given in Fig. 1 and the calculated emissivities for the shock are given in Table 2.

Table 1

Electron Density

p_1 mm Hg (measured)	M_S (measured)	N electrons/cc (calculated)
0.8	12.3	8×10^{15}
3.5	10.9	7×10^{15}
8.5	9.7	6×10^{15}
25	8.7	5×10^{15}

For the noise radiation a normal 3 cm crystal mixer superhet receiver was used. Its overall noise figure was 14 dB. The local oscillator was set to the frequency of the klystron in the emissivity measurement. The second horn was terminated with a matched load.

Typical traces of the second detector output are given in Fig. 2. From the part of the trace when there is no shock, an idea of the noise level of the receiver can be obtained. Since the effective noise figure for receiving noise was 11 dB, a spread in the measured temperatures of around 3600°K might be expected. Corrections for signals received from colder parts of the apparatus are small compared with this.

5. Discussion of Results

Bearing in mind this inherent limitation of the particular receiver used and the fact that no correction has been made for the loss of noise signal in the horn section joining the shock tube to the receiver, the results in Table 2 agree reasonably well with Frood's calculated values. It would be expected that at the shock front the temperature* should tend towards the zero ionisation value and later that the equilibrium temperature should be reached.

The temperature traces in Fig. 2 are quite typical of the 20-30 temperature observations that were made. There is an initial peak followed by a dip and a final rather smaller peak. The final peak is largely due to the better match that occurs near the contact surface, possibly as the boundary layer thickens. The initial peak has a genuinely higher temperature than the rest of the trace.

Perhaps the surprising thing about these results is the high emissivity values that were measured, even although the densities ($N = 10^{15}$-10^{16} electrons/cc) are vastly greater than the critical density (10^{12} per cc).

The reason that so dense a plasma matches to the receiver is the high collision frequency. Its significance can be seen if we take the simple conductivity expressions for an ionised gas. These are based on the very naïve assumption that the collision frequency of electrons with atoms is independent of the electron velocity. It has been shown[3] that

at/

---

*The word temperature should not strictly be applied to a non-equilibrium state. There is an excess of kinetic energy at the shock front which is reduced by several mechanisms including ionising collisions and microwave radiation.

at microwave frequencies the simple Lorentz theory gives results which within experimental limits are not distinguishable from more exact treatments. The conductivity expression is

$$\sigma = \frac{Ne^2}{m} \cdot \frac{\nu - i\omega}{\nu^2 + \omega^2} \qquad \ldots(1)$$

where N is the number density of electrons

e and m are their charge and mass

ν is their collision frequency with atoms

and ω is the angular frequency of the microwave signal.

From this expression a complex dielectric constant can be formed

$$\frac{\epsilon}{\epsilon_o} = 1 - \frac{i\sigma}{\epsilon_o \omega}$$

$$= 1 - \frac{\omega_p^{\,2}}{(\omega^2+\nu^2)} + \frac{i\omega_p^{\,2}\nu}{(\omega^2+\nu^2)\omega}, \qquad \ldots(2)$$

where ϵ_o is the permittivity of vacuum and $\omega_p = \left(\frac{Ne^2}{m\xi}\right)^{\frac{1}{2}}$ is the critical frequency. Space propagation of a wave will vary as

$$\exp ikx = \exp i \frac{2\pi x}{\lambda} \left(\frac{\epsilon}{\epsilon_o}\right)^{\frac{1}{2}}, \qquad \ldots(3)$$

where k is the propagation constant and λ is the free space wavelength.

The dielectric constant (ϵ) and refractive index (n) of the medium can be expressed as complex numbers

$$\left.\begin{aligned} n &= \epsilon^{\frac{1}{2}} \\ \epsilon &= \epsilon' + i\epsilon'' \\ n &= n' + in'' \end{aligned}\right\} , \qquad \ldots(4)$$

whence the components that determine the propagation conditions in equation (3) are

$$n' = \frac{1}{\sqrt{2}} [\epsilon' + (\epsilon'^2 + \epsilon''^2)^{\frac{1}{2}}]^{\frac{1}{2}}$$

$$n'' = \frac{1}{\sqrt{2}} [-\epsilon' + (\epsilon'^2 + \epsilon''^2)^{\frac{1}{2}}]^{\frac{1}{2}}. \qquad \ldots(5)$$

From (2) and (5) it can be seen that for the case $\nu = 0$, n' reduces to zero for $\omega = \omega_p$. This is the usual plasma resonance condition. In waveguide parlance this is a cut off condition, with the phase change in the medium becoming zero. For the conditions in the shock tube however, $\nu \simeq \omega$ at the lowest pressure and exceeds this value

at/

at the higher three pressures. When $\nu = \omega = \omega_p$ the value of n' reduces to 0.77. Thus the wave is no longer totally reflected at the plasma boundary and at the same time the finite value of n'' means that there is wave attenuation and hence matching.

Matching is further improved by the fact that at the boundary the electron density is zero. It increases in the form of a zero order Bessel function with a maximum on the shock tube axis. Thus the plasma behaves as if it had a metallic core surrounded by a lossy dielectric which absorbs a signal and emits microwave noise.

There is of course a danger that the microwave will be matched into a cooled boundary layer, which will certainly happen in extreme cases. It does not appear to have occurred in this experiment since the measured temperatures of Table 2 agree with the theoretical values within experimental error, if a reasonable estimate for the loss down the waveguide horns is made. The electron temperature is only reduced over a much thinner region than the normal boundary layer because of the small energy change on collision with atoms. In this thin region, the density is very low so that interaction with the cooled electrons should be small in most cases. There is a similar physical reason why it is possible to use the same positive column noise source as a calibration standard for microwave receivers of very different frequencies. The electron density on the axis is usually greater than critical, and different microwave frequencies match into different depths of the discharge. This is possible because of the Bessel function density distribution, which also ensures that the match is good. However the radial temperature variation seems to be quite negligible, both in theory and experiment.

6. Conclusion

It has been shown that it is possible to get some information on the temperatures in shock-tube plasmas from the radiated microwave noise. Less hurried measurements should give more accurate results. A well made receiver should have a noise level 6 dB lower than was used in these experiments. The loss down the horns could be measured by a subsidiary experiment. The particular advantage of this measurement would be the short resolving time (order 1 microsecond).

Acknowledgement

This work was done during a vacation consultancy in the Aerodynamics Division of the National Physical Laboratory. It is a pleasure to acknowledge the help and advice of many members of the Division, particularly Dr. D. L. Schultz, Dr. K. C. Lapworth, Dr. L. Pennelegion and Mr. K. Moreton who also assisted with the measurements. The collaboration and loan of some microwave equipment by Mr. J. S. T. Looms and Mr. P. Barber of the Central Electricity Generating Board Research Laboratories was also a great help.

Table 2/

Table 2

Electron Temperature

p_1 mm Hg (Meas)	Emissivity at 3 cm wavelength			Measured Temperature °K			Calculated Temperature (Frood) (°K)	
	Shock front	Middle	End	Shock front	Middle	End	No ionisation	Equilibrium
0.8	0.37	0.76	0.60	11000	2300	3200	14,200	10,000
3.5	0.62	0.59	0.89	5900	3600	2900	11,200	9,400
8.5	0.56	0.54	0.87	9200	6300	7100	9,100	8,300
25	0.80	0.85	0.85	6200	4100	4100	7,200	7,200

Table 3

p_1 (mm Hg)	ρ_2/ρ_1	ℓ (theory) (cm)	τ (theory, corrected) (microsec)	$\tau_{meas.}$ (microsec)	$\frac{\tau_{theory}}{\tau_{measured}}$
0.8	5.8	57.8	225	70	3.20
3.5	4.75	70.5	310	150	2.05
8.5	4.05	82.5	420	215	1.95
25	3.85	87.0	490	280	1.75

APPENDIX/

APPENDIX

Duration of Shock Flow

The ionised gas occupies the region between the shock front and the contact surface. This length (ℓ) is zero at the diaphragm but after the shock has travelled a distance x along the shock tube, all the gas that was initially at pressure p_1 in this distance is compressed into the length ℓ. Mass is conserved, therefore

$$\rho_1 x = \rho_2 \ell \qquad \ldots(6)$$

where ρ_1, ρ_2 are the initial and shock densities respectively. The time duration of the shock flow can be defined as

$$\tau = \frac{\ell}{U_c} \qquad \ldots(7)$$

where U_c is the contact surface velocity. From the continuity equation

$$\rho_2 (U_S - U_C) = \rho_1 U_S \qquad \ldots(8)$$

equation (7) becomes

$$\tau = \frac{x}{\left(\frac{\rho_2}{\rho_1} - 1\right) U_s}$$

$$= \frac{x}{\left(\frac{\rho_2}{\rho_1} - 1\right) aM_s} \qquad \ldots(9)$$

where U_s is the shock front velocity

M_s is the measured shock Mach number

and a = 314 m/sec is the velocity of sound in argon.

Values of ℓ and τ calculated from equations (6) and (9) are given in Table 3. The correction to τ is an increase to allow for the fact that in the experiment the waveguide horns straddle 11 cm of the tube, which is an appreciable fraction of the shock length, ℓ.

The fact that measured shock durations are shorter than the theoretical times is well known and the greater discrepancy at low pressures has also been remarked[4].

The measured times are rather longer than those observed recently by Roshko[5] using fine wires as the shock detectors. Possibly the microwave times are too long because of the delayed creation of electrons by collisions involving meta-stable argon ions[6]. It would be of interest to compare microwave and thermal times in a simultaneous experiment.

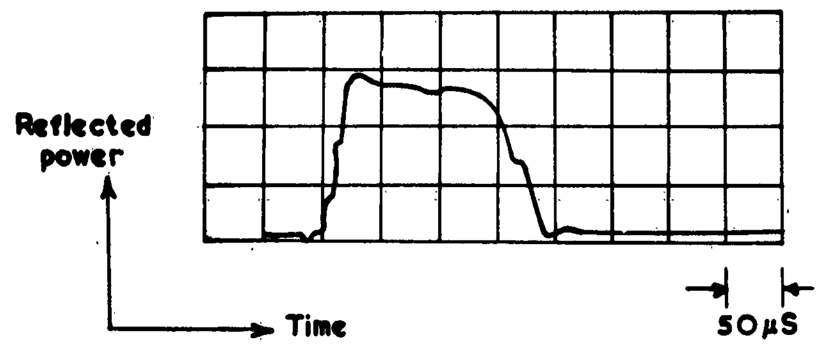
References/

References

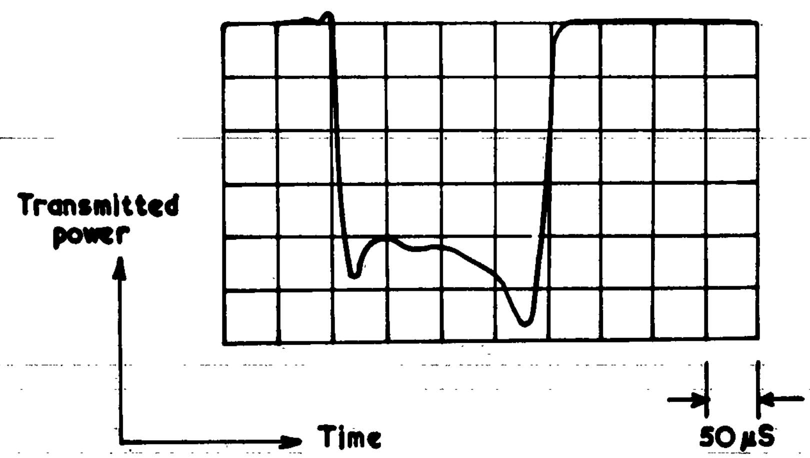
No.	Author(s)	Title, etc.
1	D. L. Schultz	Microwave techniques applied to the investigation of ionised gases in shock tubes. A.R.C.20,203 - F.M.2685. 29th May, 1958.
2	D. G. H. Frood	Ionising shock waves in monatomic gases - with application to argon. R.R.E. Memo. No.1305. 1956.
3	E. M. Bradley and D. H. Pringle	The theory and design of gas discharge microwave attenuators. J.Brit.I.R.E. 15, 11, 1955.
4	R. E. Duff	Shock tube performance at low initial pressure. Phys. Fluids, Vol.2, Pt. 2, March/April, 1959, pp.207-216.
5	A. Roshko	On flow duration in low pressure shock tubes. Phys. Fluids 3, 835, 1960.
6	M. A. Biondi	Phys. Rev. 83, 1087, 1951.

ES

22,930.
FIG.1.



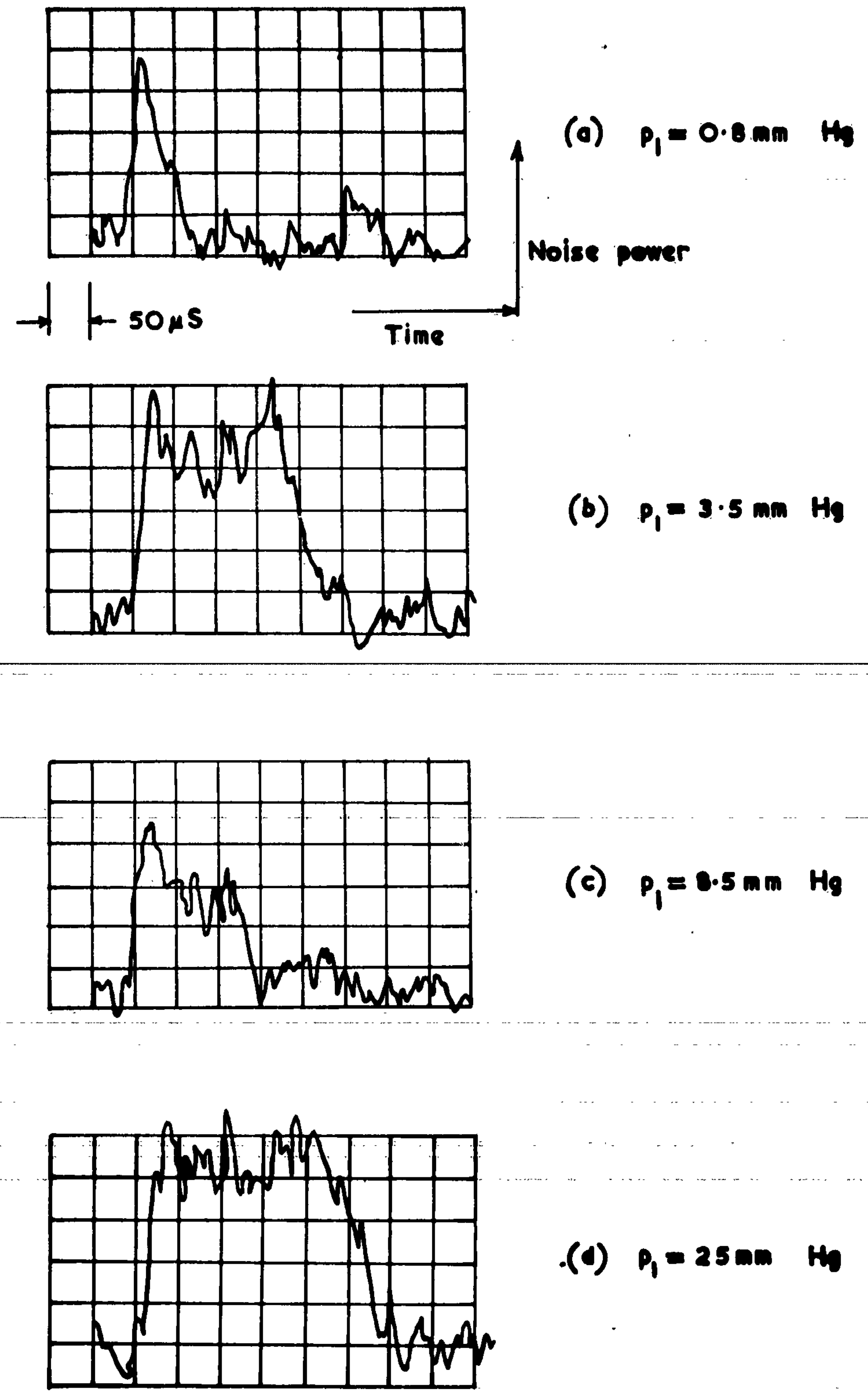
(a) Reflected pulse



(b) Transmitted pulse

Reflected and transmitted pulses with $p_1 = 8 \cdot 5$ mm Hg, $M_s = 9 \cdot 7$.

22,930.
FIG.2.



Microwave noise radiation. Output current of second detector.

DETACHABLE ABSTRACT CARDS

These abstract cards are inserted in A.R.C. Reports for the convenience of Librarians and others who need to maintain an information index.

Detached cards are subject to the same Security Regulations as the parent document, and a record of their location should be made on the parent document.

UNCLASSIFIED

A.R.C. 22,930
13.6.61
Walsh, D. University of Oxford

THE MEASUREMENT OF TEMPERATURE IN AN ARGON SHOCK TUBE BY MICROWAVE NOISE RADIATION

Experiments with argon in a 2 in. shock tube at the N.P.L. have shown that it is possible to get some information on the temperatures in shock-tube plasmas from the radiated micro-wave noise.

UNCLASSIFIED

UNCLASSIFIED

A.R.C. 22,930
13.6.61
Walsh, D. University of Oxford

THE MEASUREMENT OF TEMPERATURE IN AN ARGON SHOCK TUBE BY MICROWAVE NOISE RADIATION

Experiments with argon in a 2 in. shock tube at the N.P.L. have shown that it is possible to get some information on the temperatures in shock-tube plasmas from the radiated micro-wave noise.

UNCLASSIFIED

UNCLASSIFIED

A.R.C. 22,930
13.6.61
Walsh, D. University of Oxford

THE MEASUREMENT OF TEMPERATURE IN AN ARGON SHOCK TUBE BY MICROWAVE NOISE RADIATION

Experiments with argon in a 2 in. shock tube at the N.P.L. have shown that it is possible to get some information on the temperatures in shock-tube plasmas from the radiated micro-wave noise.

UNCLASSIFIED

UNCLASSIFIED

A.R.C. 22,930
13.6.61
Walsh, D. University of Oxford

THE MEASUREMENT OF TEMPERATURE IN AN ARGON SHOCK TUBE BY MICROWAVE NOISE RADIATION

Experiments with argon in a 2 in. shock tube at the N.P.L. have shown that it is possible to get some information on the temperatures in shock-tube plasmas from the radiated micro-wave noise.

UNCLASSIFIED

[dstl]

Defense Technical Information Center (DTIC)
8725 John J. Kingman Road, Suit 0944
Fort Belvoir, VA 22060-6218
U.S.A.

AD#: AD273610

Date of Search: 22 July 2009

Record Summary: DSIR 23/28767
Title: The Measurement of Temperature in an Argon Shock Tube by Microwave Noise Radiation
Availability Open Document, Open Description, Normal Closure before FOI Act: 30 years
Former reference (Department) ARC 22930
Held by The National Archives, Kew

This document is now available at the National Archives, Kew, Surrey, United Kingdom.

DTIC has checked the National Archives Catalogue website (http://www.nationalarchives.gov.uk) and found the document is available and releasable to the public.

Access to UK public records is governed by statute, namely the Public Records Act, 1958, and the Public Records Act, 1967.
The document has been released under the 30 year rule.
(The vast majority of records selected for permanent preservation are made available to the public when they are 30 years old. This is commonly referred to as the 30 year rule and was established by the Public Records Act of 1967).

This document may be treated as <u>UNLIMITED</u>.